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Recent advances in the global rare earth supply chain

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Abstract

The current global rare earth element (REE) supply chain is highly imbalanced and tightly controlled by just a few countries. Such an imbalance of the critical metals supply chain poses a significant challenge to the energy-transition strategies and the national security of many countries. This issue of the *MRS Bulletin* delves into the material science aspects of the REE supply chain, including fundamental REE mineralogy, REE separation and extraction, REE mining economics, the environmental impacts of REE mining and processing, and circular economy potential for REEs. This issue of the *MRS Bulletin* is meant to inform the materials science community of some of the constraints on REE production from the mining of ore deposits, through processing technologies, and then finally, the possibility of recycling.

Keywords: rare earths, mining, extraction, processing, separation, circular economy

Introduction

With China's rapid rise and the reemergence of Russia as a major power, the global stage is set for multipolar competition to secure the critical metals supply chains and control the rare earth elements (REEs) derived high-end products and relevant technologies (**Figure 1**). Among these critical metals, which include cobalt, nickel, copper, and lithium, the REEs are among the most hotly contested. The REEs are much less rare than precious metals, such as gold, silver, and platinum, but mineable concentrations are less common than for most other mineral commodities. The estimated average concentration of the REE in Earth's crust ranges from around 130 µg/g to 240 µg/g. [1] The majority of the world's REE reserves are located in China (36.66%), Brazil (17.50%), Vietnam (18.33%), Russia (10%), and India (5.75%), whereas the United States hosts only 1.25% REE reserves worldwide. Similarly, China (58.33%), the United States (15.83%), Burma (12.5%), and Australia (7.1%) were the world's largest REE producers in 2020 [2].

REEs comprise as single row of 14 elements (Z = 57 to 71) with a similar electronic structure and a single, trivalent oxidation state, Ln_2O_3 (except for Ce, which can also occur as Ce(III) or Ce(IV). For the majority of the neutral lanthanide atoms, the electronic configuration is: [3] $4f^{n+1}$, $5s^2$, $5p^6$, $6s^2$. With increasing Z, there is a slight contraction of the ionic radii (0.139 nm to 0.1 nm); hence rare earths often occur as complex solid solutions, such as in bastnäsite ($REE(CO_3)(OH/F)$) or xenotime ($Y(PO_4)$), and may contain significant amounts of thorium as an impurity. In the absence of multiple oxidation states, chemical concentrations of metals as ore bodies in Earth's crust are rare, and the number of ore deposits is less abundant. As an example, monovalent thorium occurs less often in ore deposits than polyvalent uranium that can be concentrated by changing redox conditions during ore formation.

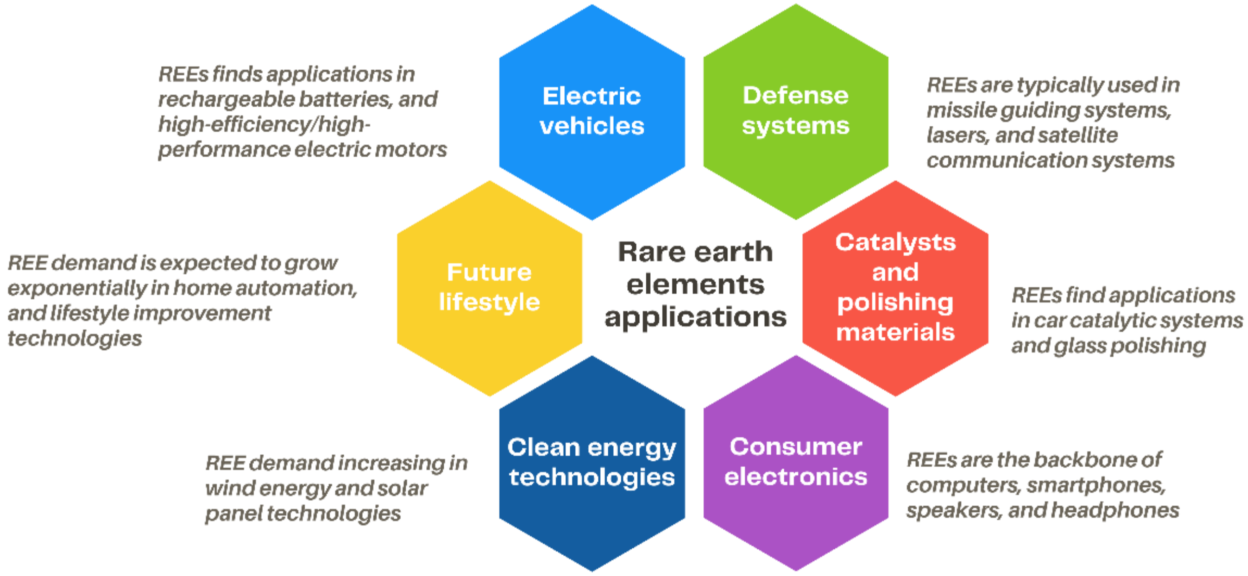

Figure 1. Rare earth elements (REEs) are important in energy transitions, national security, and consumer electronics applications.

Major deposits of rare earths are located in China, Brazil, and Vietnam, accounting for 72.5 % of the world's rare earths reserves. According to the recently published US Geological Survey's Minerals Commodity Summaries 2021 report, China led the world's 2020 rare earths mine production with a hefty share of ~58%. [2] Further, China also processes REE ore from other countries, such as the United States, thus providing more than 80% of the world's processed REEs. [4] In turn, China strategically leverages various drivers to tightly control the global rare earth supply chain (**Figure 2**).

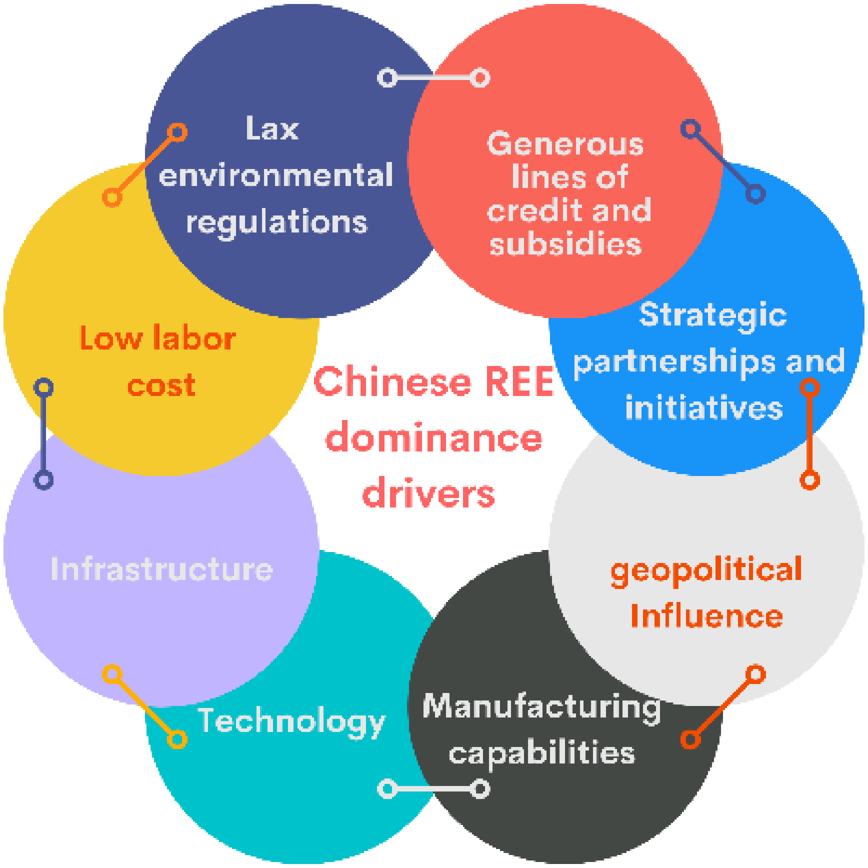

Figure 2. China uses strategic drivers to tightly control the global rare earth elements supply chain.

REE applications and the global initiatives to develop an alternative REE supply chain

The imbalance in critical materials supply chains poses a significant challenge to advancing many emerging, strategic, and sustainable technologies worldwide. While the sources of REEs are slowly expanding, the REEs are finding more applications. For instance, an F-35, all-weather stealth multirole combat aircraft requires an astonishing 417 kg of REEs that are mainly used in the electrical components and permanent magnets of the aircraft. Disruption in the REE supply chain could affect the development and production of F-35 aircraft. [5]

The REEs also constitute a crucial component of electric vehicle (E.V.) motors (e.g., neodymium magnets, such as NdFeB). Currently, the United States has 270 million cars running on gasoline. However, only 2 million cars (or roughly 0.75% of the total cars) in the United States are currently electric. [6] Therefore, a migration from conventional cars into electric cars, even in a smaller fraction, may require a significant amount of REEs that the United States does not produce currently. Based on Deloitte’s recent report, the worldwide E.V. market is projected to grow at a compound annual growth rate of 29% by 2030. [7] Such growth is great news to the recently discussed United Nations (U.N.) climate goals during the COP26 conference. [8] The new US E.V. car share is projected to increase 27% by 2030. At least seven times the amount of rare earth metals will be needed to meet such ambitious goals, yet this could be a challenge, particularly due to the current uncertain global geopolitical environment. Interestingly, due to its multidimensional strategic actions, China is expected to lead the worldwide E.V. market by 2030 with a 49% market share, followed by Europe (27%) and the United States (14%). [7]

Consequently, multifaceted national initiatives have been designed to respond to the growing demand by discovering new ore deposits, finding substitute elements for specific applications, developing highly efficient REE separation and extraction technologies, or recycling end-of-life (EOL) products. The United States Department of Energy (DOE) sponsors a Critical Materials Institute (CMI) led by Ames National Laboratory and supported by multiple national laboratories and several dozen universities and industrial partners. The DOE established the CMI in 2013 with initial funding of $120 million for five years. Subsequently, the CMI was renewed until 2023 with $30 million of annual funding. The CMI prioritizes critical materials research, development, and demonstration (RD&D) to diversify supply, develop substitutes, improve reuse and recycling, and encourage cross-cutting approaches to develop new research tools and forecast what materials might become critical in the future. Interestingly, recent legislation, including the US Infrastructure Investment and Jobs Act (H.R.3684), is also providing much-needed support ($0.6 billion) to carry out critical metals innovation, efficiency, and alternative development activities. However, in the global context and considering the fierce geopolitical competitions with China and Russia, such levels of support are small and may not be sufficient to address the critical metal supply chain challenges that the United States currently faces. There are some recent announcements from the United States government to increase the level of financial support. [9]

In contrast, China is strategically backing its critical materials supply chain industries with significant lines of credit. According to the recent New York Times report, [10] the top five Chinese mines in the mineral-rich Democratic Republic of Congo were given a $124 billion line of credit from the Chinese state-owned banks. Further, China also recently consolidated several state-owned rare earth companies to form a larger company that can better control the REE supply chain. [11] Such consolidation is expected to provide better management, reduce the competition between domestic entities, address environmental issues, develop highly efficient REE separation and extraction technologies, and control the REE-derived high-end product global market.

Additionally, China has aggressively made inroads into various lucrative undeveloped markets. China has established its presence in Africa and is currently attempting to engage with many African countries to secure long-term REE mining contracts. [12] A similar effort is also being pursued in South America. [13] Further, China is trying to fill the void left by the United States by acquiring the strategic rare earth metals in Afghanistan. [14] Finally, China is also trying to leverage its position to boost its presence in the Arctic region. [15] This serves as a warning to the United States and other countries trying to develop an alternative supply, as China has capitalized on the past domestic and foreign policies in the United States and its strategic partners. For instance, the United States Nuclear Regulatory Commission (NRC) and the International Atomic Energy Agency (IAEA) amended their definition of source material (or the materials containing thorium and uranium) that brought heavy rare earth (RE) byproducts into the source material category, which, in turn, placed heavy RE under extensive licensing, regulatory, disposal, and liability rules. [16] This development added to the cost and liabilities of heavy RE processing, resulting in a termination of heavy RE production and refinement in the United States.

On the other hand, China, as an observer and not a member of the IAEA, capitalized on this opportunity and replaced the United States in the production and processing of rare earths. Moreover, the United States Congress granted China a most favored nation status in 1980. This enabled transfer of goods, knowledge, and technology to China. In turn, China complemented the rare earth processing technology with lower production and labor costs, generous state subsidies, and lax environmental regulations and established dominance of the REE supply chain. [16]

Many other countries, including the United Kingdom [17], Australia [18], and the European Union (E.U.) [19], have already created initiatives to develop alternative critical metal supply chains that are free from Chinese influence. For instance, the E.U. sponsored the *Secure European Critical Rare Earth Elements* (SecREEts) [20] to develop a reliable and uninterrupted supply of REEs and reduce REEs reliance on the foreign competing economies. The SecREEts project started in June 2018 and is slated to continue until 2022. The main objective of the SecREEts project is to establish a stable and secure supply of critical REEs based on sustainable extraction of REEs from European apatite sources used in fertilizer production. [20]

In this issue

This issue of the *MRS Bulletin* consists of six articles that delve into the material science aspects of the REE supply chain (**Figure 3**). Specifically, we feature articles on REE mineralogy, REE separation and extraction, REE mining economics, environmental impacts of REE mining and processing, and the REE recycling and circular economy.

Figure 3. A typical rare earth elements supply chain process flow diagram.

The first article by Ciobanu et al. [21] provides fundamental insights into the mineralogical properties of REEs. Further, Ciobanu et al. [21] use the high angle annular dark-field scanning transmission electron microscopy (HAADF STEM) atomic-scale visualization technique to show the highly irregular domains featuring atomic-scale REE intergrowths of bastinäsite and synchysite ($CaREE(CO_3)_2F$) abundant in the Olympic Dam deposit in Australia. Understanding bastinäsite and synchysite require a stepwise analytical approach to link micron and nanoscale observations. The insights provided by Ciobanu et al. [21] have implications for understanding the genesis and evolution of breccia-type deposits and the phase stability of bastinäsite and synchysite mineral groups. This approach can help to fully exploit the future potential of mines similar to the Olympic Dam mine deposit in Australia.

Thorium and uranium management from REE waste products pose a threat to human health and the environment. More efficient processing technologies could enhance the production yield, lower production costs, and minimize the waste generated during the REE processing. McNulty et al. [22] review past and current REE processing technologies commonly used for REE separation and suggest future REE processing efficiencies.

The various environmental impacts associated with REE processing and recovery are significant concerns for regulators. Each stage involved in the REE recovery chain (e.g., mining, beneficiation, separation) is associated with one or more possible environmental hazards. For instance, mine blasting contributes to particulate matter formation and ionizing radiation from thorium impurities. Such environmental impacts can be mitigated with the appropriate operational changes (e.g., utilization of an irrigation system) that can reduce the rate of dust formation. Zapp et al. [23] discuss the environmental impacts associated with REE processing. In particular, the life cycle assessment (LCA) technique is used to estimate the environmental impacts—including greenhouse gas generation, acidification, eutrophication, and toxicities—associated with the REE production activities (e.g., REE mining, processing, and extraction). The LCA assessment provides an initial insight during the basic evaluation of the possible environmental impacts associated with the REE supply chain. Zapp et al. [23] also discuss the possible technology optimizations and environmental safety strategies required to minimize the environmental impact in REE recovery.

Economics is another crucial factor in developing a new mine and guiding mining exploration. A new mining project is a long-term commitment that lasts on the order of 30–40 years. Many investors shy away from the REE mining industry due to the limited market capitalization of REE industry and the volatility of REE prices. Jowitt [24] reviews the mineral economics of the REES and the “balance problem.” The “balance problem” is the balance between the abundance of the rare earth elements in ores and their demand. The REE supply and demand depend on the market needs, where some REEs (e.g., neodymium) are in higher demand than others. Consequently, REEs in high demand are produced more, whereas REEs in low demand are stockpiled. Therefore, the REE economic analysis is vital in assessing costs associated with the REE separation, recovery, and stockpiling that influence the economics of REE production.

REE recycling is no longer just a choice, but it has become necessary in a world where resources are constrained. The REE demand from various industries is predicted to soar, as is their recovery by recycling. Presently, only 1% of the REEs are recycled. [25] The collection and disassembly of components are bottlenecks in REE recycling. Recycling could potentially avoid multiple challenges, including eliminating the need for new mines, reducing the impact on the environment, and addressing the balance problem (i.e., the least valuable REE constitute the majority of REE ores). Fujita et al. [26] examine the recycling of REEs. In particular, the vital components of the REE supply chain and a source of the REEs are discussed, which can lower the barriers on the administrative, logistic, and economic hurdles of opening new mines. Fujita et al. [26] also summarize some recent developments in REE recycling at the CMI and outline the long-term strategy for sustainable recycling.

Finally, Swain [27] sheds light on the prospects of a circular economy for REEs. As an example, there is a large, untapped, REE secondary resource of REEs associated with the production of aluminum. Red mud from aluminum production is an industrial waste that could be a significant source of rare earth metals. Swain provides a comprehensive estimate of REEs in globally stockpiled red mud. Swain calculates that the 9.14 million tons of rare earths remain locked in the stockpiled red mud as of 2019.

Overall, current mining processing operations allow 50–80% REE recovery. The expectation is to leverage the ongoing scientific research to enhance the REE recovery by developing more powerful and selective reagents, more efficient concentrating devices, and models that fully integrate processing flowsheets. Further, the life cycle assessment (LCA) technique can mitigate the environmental problems related to the large quantities of chemicals needed to process REEs and the large quantities of tailings generated during extraction, separation, and beneficiation that contain the naturally occurring radionuclides, mainly thorium. Finally, the recycling of EOL products is expected to grow significantly as a future source of REEs.

Future outlook

The world is changing, as are the technological and geopolitical landscapes. Many countries are leveraging the critical minerals supply chain as a bargaining chip to lead the race to technological innovation. [17] Tension between China and Japan in 2010 has highlighted the vulnerability of nations on other nations for critical metals. [28] These events are a warning to the United States and other countries that rely on China for REEs and who are trying to establish an alternative supply chain that is uninterruptable and environment friendly.

Consequently, the United States and other countries should take a few immediate actions to reduce the dependence on Chinese REEs and develop an alternative REEs supply chain (**Figure 4**). First and foremost, the United States should stockpile rare earths to support the defense technologies critical for national security. Recently, Japan has extended its stockpile of critical materials from 60 days to 180 days of domestic consumption. [29] The United States should adopt a similar strategy. Second, the United States should revisit the stringent mining and environmental policies and address the bottlenecks in promoting sustainable mining practices in the United States. The United States government has recently taken initiatives in this direction. [9] For instance, the MP materials received $35 million from the Industrial Base Analysis and Sustainable Program of the United States Department of Defense. MP Materials will process heavy REE and domestically establish a permanent magnet supply chain. Further, the United States Department of Energy, contingent upon an award from the Bipartisan Infrastructure Law (BIL) funding, will launch a $140 million demonstration project to separate REE and critical metals from coal ash and other mine waste. [9]

Similarly, the United States Department of Interior is planning to convene a meeting and invite stakeholders to review and reform the mining laws, regulations, and permitting. [30] Also, the United States Department of Interior will launch interagency groups to facilitate the potential rulemaking efforts and support the United States vision to promote a sustainable domestic critical material supply chain.

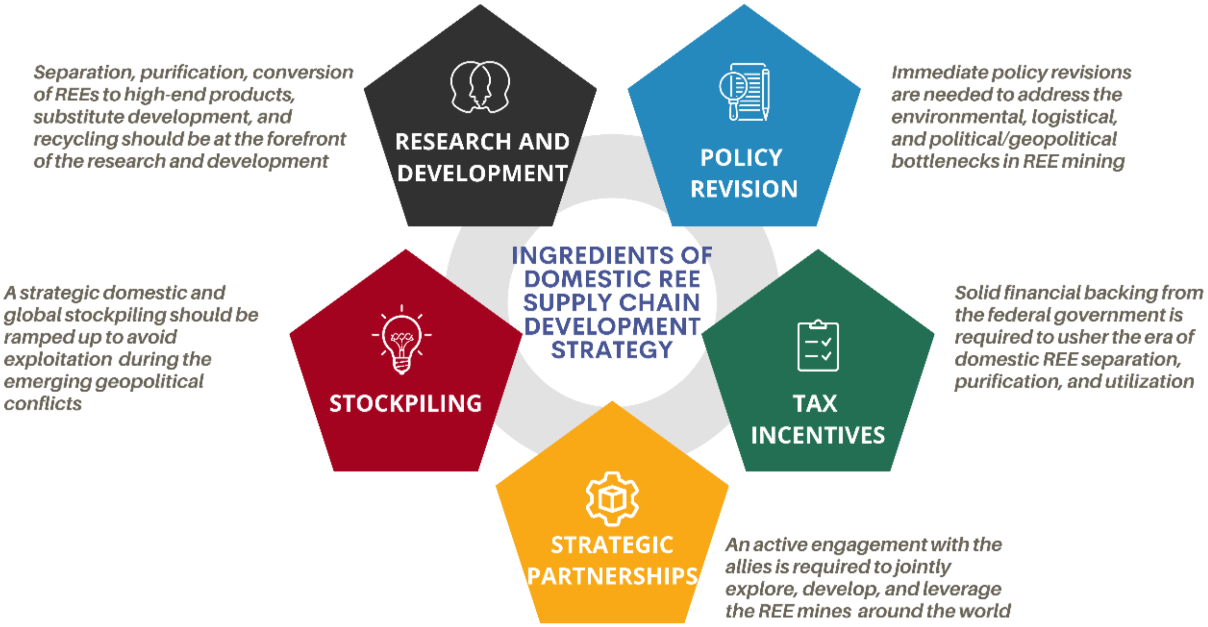

Figure 4. The multiprong approach is required to develop an alternative rare earth elements (REE) supply chain.

Finally, the United States Department of Defense, Department of Energy, and Department of State signed a memorandum of agreement to coordinate the critical metals stockpile efforts and support the United States’ transition to clean energy and national security needs. The stockpile guidance is expected to release in the coming days. [31] In turn, various government initiatives announced recently are important and will improve the US strategic position. [32] Finally, the United States should proactively engage with its allies to leverage collective strategic, technological, and economic capabilities to develop an alternative critical material supply chain. Some initiatives were discussed on the sidelines of the recent COP26 conference. [8] However, a significant push is necessary to urgently and frequently bring nations to the table and develop a strategy to fight against climate change by developing technologies that can sustain energy transitions away from fossil fuels.

Conflict of interest

G.P. and R.E. state that they have no conflict of interest related rare earth elements as discussed in this paper.

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